Global climatology of Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) in ERA-40 reanalysis

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ABSTRACT

Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN) play a dominant role in convective precipitation, its genesis and intensity. A global climatology of CAPE and CIN is presented in terms of seasonal means, variances, and trends based on 44 years (1958–2001) of six-hourly ERA-40 reanalysis (European Centre for Medium-Range Weather Forecast ECMWF, T106 resolution). CAPE shows large values and high variability in the tropics with maxima over the continents; the seasonal changes are dominated by specific humidity. CIN shows large means and variability in the subtropics. Significant trends in CAPE and CIN give the following results: (i) In general, a CAPE increase is noted during all seasons while, in particular, in autumn CIN shows a decrease over continents. (ii) Splitting of the time series reveals a sign change in trend commencing at the end of the 70s; this is observed in parts of the tropical continents and North America. CAPE and CIN show trends of opposite sign with CAPE increasing in the first half and a decrease during the second half (and vice versa for CIN).

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Keywords:
CAPE
CIN
ERA-40
Trend analysis

1. Introduction

Precipitation variability affects water resources in past, present, and future climates. For convective precipitation, and severe weather analysis and forecasting the parameter CAPE (Convective Available Potential Energy) is used (e.g. Rasmussen and Blanchard, 1998; Craven et al., 2002; Markowski et al., 2002; Brooks et al., 2003; Brooks et al., 2007; Brooks and Evans, 2003). CAPE is also used in cumulus parameterisation in general circulation models (e.g. Moncrieff and Miller, 1976; Washington and Parkinson, 2005; Ye et al., 1998). In connection with its opposing parameter CIN (Convective Inhibition) CAPE is a candidate for analysing convective precipitation variability. In this sense CAPE and CIN climatologies provide a deeper insight into genesis and intensity of atmospheric convection. Part of this climatology comprises seasonal means, variances, and trends. As CAPE variations in space and time are dominated by regional changes in boundary layer temperature and humidity (Ye et al., 1998; Yano et al., 2001), temperature and specific humidity near the surface are also analysed.

Global CAPE climatologies have been derived from seven years NCEP/NCAR reanalyses (National Centre for Atmospheric Research (NCAR)/United States National Centres for Environmental Prediction (NCEP), Brooks et al., 2003, 2007). For Europe, thirty year climatologies of CAPE and CIN have been computed (Romero et al., 2007) based on ERA-40 (European Centre for Medium-Range Weather Forecast (ECMWF)). For the United States, these studies are supplemented by CAPE climatologies of present day and future scenarios simulations by several coupled atmosphere and ocean models (Trapp et al., 2007). We complete the CAPE and CIN analyses by global climatologies based on 44 years of ERA-40 data, to provide seasonal ensemble means of first and second moments, and a trend analysis.

The outline of the paper is as follows: the data and method of analysis (Section 2), which includes calculation of CAPE...
and CIN (Sections 1 and 2) is followed by the presentation of the CAPE and CIN climatologies results (Section 3). Section 4 presents conclusions and gives an outlook on future research on higher order statistics.

2. Data and methods of analysis

The thermodynamical parameter CAPE describes the potential buoyancy available to idealised rising air parcels and thus denotes the instability of the troposphere (Blanchard, 1998). CIN describes a stable surface layer, which rising air parcels need to overcome to reach the instable layer described by CAPE (further definitions see below).

Surface based CAPE is calculated pseudo adiabatically from temperature (T) and relative humidity (RH) fields on 13 vertical pressure levels between 1000 hPa and 100 hPa. These parameters are derived globally from ERA-40 datasets (Källberg et al., 2004) on a horizontal grid spacing of approximately 1.125° four times a day from 1958 to 2001. The surface pressure field is used to filter out extrapolar pressure levels; thus in regions with high topography (for example, the Tibetan Plateau) all pressure levels below topography are omitted in the CAPE calculation.

The ERA-40 data is the most recent reanalysis which covers a time period longer than 44 years (September 1957 to August 2002). Although ERA-40 data are generally of high quality, differences may occur due to the varying density of observations (as in the southern hemisphere, and over oceans). From 1978 satellite measurements are taken into account in the data set, improving the quantity and quality of measurements considerably (Uppala et al., 2005). Therefore, we focus on continental regions in the northern hemisphere during the whole period of time and on a global distribution after 1978. Although satellites improve the data, the change in the measurement system leads to an artificial warming trend in the global mean temperature of the lower troposphere (Bengtsson et al., 2004). The differences between observed and ERA-40 temperature trends are also pointed out by Simmons et al. (2004). However, ERA-40 data yield the general trend signal with an improving performance after 1978. Thus, trends in CAPE and CIN are analysed for the whole period of time and additionally before and after 1978.

2.1. CAPE

CAPE is defined as the positive temperature difference between an idealised rising air parcel \( T_{vp} \) and its environment \( T_{ve} \) within two specific height levels multiplied with the gas constant of dry air \( R_d \) (Emanuel, 1994).

\[
\text{CAPE} = \int_{\text{LNB}}^{\text{LFC}} R_d \left( T_{vp} - T_{ve} \right) \, d\ln(p)
\]  

As moisture is taken into account the virtual temperature \( T_v \) is used. The air parcel rises dry adiabatically from the surface to the lifting condensation level (LCL). Above the LCL the parcel rises pseudo adiabatically which means that condensed moisture will immediately fall out of the parcel as rain. CAPE is calculated between the level of free convection (LFC) and the level of neutral buoyancy (LNB) referred to as bottom and top of the cloud. Between cloud bottom and cloud top the parcel rises freely as the temperature of the parcel is higher than the temperature of its environment. The pseudo equivalent potential temperature \( \Theta_{ep} \) remains constant during a pseudo adiabatic ascent and, therefore, is used to calculate the temperature of the rising parcel (Emanuel, 1994).

\[
\Theta_{ep} = T \left( \frac{p_{ep}}{p} \right)^{0.2854 (1 - 0.28r)} \exp \left[ r (1 + 0.81r) \left( \frac{3376}{T_{LCL}} - 2.54 \right) \right]
\]  

with the mixing ratio \( r \) of dry to moist air and the temperature \( T_{LCL} \) of the parcel at the LCL, where the ascent of the air parcel changes from dry adiabatic to pseudo adiabatic. The saturation temperature \( T_{LCL} \) is approximated (Bolton, 1980) by

\[
T_{LCL} = \frac{2840}{3.5 \log T_{sfc} - \log e - 4.805} + 55
\]

with the vapour pressure \( e \).

2.2. CIN

High values of CAPE do not necessarily lead to strong convection, as the simulated air parcel needs to overcome a usually stable layer between the surface (SFC) and LFC. The intensity of this stable layer is defined by CIN. The temperature difference between the same rising air parcel as in CAPE is calculated between SFC and LFC (Williams and Renno, 1993).

\[
\text{CIN} = \int_{\text{SFC}}^{\text{LFC}} R_d \left( T_{ve} - T_{vp} \right) \, d\ln(p)
\]  

As CIN defines the energy of a parcel needed to reach the available energy above the LFC and therefore to be able to develop convection, CIN describes the limiting factor, which is able to prevent convection even though very high values of CAPE exist.

2.3. Trend analysis

Local seasonal trends in CAPE, CIN, near surface temperature, and near surface specific humidity are analysed by the Mann–Kendall trend test which is a robust trend estimator applicable for any theoretical distribution. This particular test is used here, as CAPE is not normally distributed in general. The trend in CAPE is calculated on a seasonal mean basis. Only positive CAPE values are considered in the calculation. Grid points with less than two positive CAPE values per season are neglected.

The Mann–Kendall Score indicates a given trend being positive or negative, which is supplemented by a two sided \( p \)-value to provide the probability of a detected trend (Hipel and McLeod, 2005). Trends are only included in the analysis, if their probability exceeds the 95% significance level. The magnitude of a given trend is estimated by linear regression, although the error is rarely normally distributed in CAPE.

3. CAPE and CIN climatology and trends

The global distribution of seasonal means and inter annual variances of the seasonal means of CAPE and CIN during...
1958–2001 are displayed in Section 1. Means and variances of near surface temperature and specific humidity are discussed but only partly shown.

3.1. Means and variances

The global distribution of seasonally averaged CAPE (Fig. 1) follows basically the distribution of the near surface air temperature and specific humidity (Fig. 2). CAPE values generally increase from pole to equator. CAPE minima are observed in regions of cold water upwelling and where currents are colder than the ambient ocean temperatures, and in arid regions. The comparison of zonal means suggest that specific humidity has a more pronounced influence on CAPE than temperature, indicated by a steeper pole-to-equator gradient in specific humidity than in temperature.

Fig. 1. Climatological (1958–2001) seasonal mean of CAPE in J/kg, local and zonally averaged during DJF (a), MAM (b), JJA (c), and SON (d).
(Fig. 2). Seasonally averaged values of CAPE range from 0 to about 7000 J/kg, with mean values around 300 J/kg. Largest values develop generally in the tropics close to the Inter Tropical Conversion Zone (ITCZ), where high temperatures and sufficient moisture are available.

The seasonal cycle of CAPE is defined by the seasonal cycles of temperature and specific humidity. Higher values are generally found in the summer northern hemisphere (June, July, and August, JJA) and in the summer southern hemisphere (December, January, and February, DJF). In
contrast to this general behaviour highest values occur in the 
Great Plains, the coast of India, and in the south of Chile 
during March, April, and May (MAM) due to lower moisture 
availability in JJA (Fig. 2).

Seasonally averaged values of CIN (Fig. 3) range from 0 to 
about 800 J/kg, with mean values around 20 J/kg. Largest 
values occur to the west of Senegal in MAM. In contrast to the 
zonally averaged CAPE, CIN displays a bimodal distribution.

Maxima between the equator and 30th latitude enclose a 
minimum at the equator, thus revealing the Hadley Cell. 
Ascending air at the ITCZ is shown by high values of CAPE and 
low values of CIN. The air is transported polewards and 
descends along the 30th latitude, where CAPE values are low 
and CIN values are high. The annual cycle of CIN is not as 
pronounced as in CAPE. CIN presents a similar distribution 
from June to February with larger values during MAM.
Interannual variance of the seasonal CAPE means range from 0 to about $1.8 \times 10^7$ (J/kg)$^2$, with mean values around $1.6 \times 10^5$ (J/kg)$^2$ (Fig. 4). The geographical distribution of the seasonal differences is similar to those of the seasonally averaged mean. In general, larger values are observed in summer (northern hemisphere: JJA; southern hemisphere: DJF) according to higher temperatures. However, in the Great Plains and the coast of India largest values develop in MAM due to moisture availability.

Interannual variance of the seasonal CIN means range from 0 to about $2.2 \times 10^5$ (J/kg)$^2$, with mean values around 2000 (J/kg)$^2$ (Fig. 5). In contrast to mean CIN, largest values of CIN variance occur during JJA at the west coasts of Mexico and Morocco. The annual cycle of CIN variances is similarly weakly pronounced (Fig. 5) as for CIN means (Fig. 3).

### 3.2. Trends

The CAPE and CIN trend magnitudes are displayed (Figs. 6–9) if the level of significance exceeds 95%. Trends are shown for the full 44 year time series (1958–2001) and
for the first (1958–1978) and second (1979–2001) part. However, we focus on trends in the southern hemisphere in the second part. Calculated trends before 1979 might correspond to changes in measurements instead of changes in climate (Bengtsson et al., 2004).

Significant trends in CAPE occur in most parts of the world except in Antarctica. Regions with a positive trend outnumber the regions of negative trends considerably with magnitudes varying in the time periods considered. Trend magnitudes range from about $-400 \text{ J/kg}$ to about $500 \text{ J/kg}$ per decade during 1958–2001; for the years before (only in the northern hemisphere) and after 1979 trends vary from $-600 \text{ J/kg}$ to $1300 \text{ J/kg}$ per decade. The largest increase in CAPE of about $1300 \text{ J/kg}$ per decade occurs in Mexico during JJA 1958–1978 (Fig. 7) and of about $900 \text{ J/kg}$ per decade in Gabon during MAM 1979–2001 (Fig. 6). The largest decrease in CAPE of about $600 \text{ J/kg}$ per decade is observed in Malaysia and Venezuela during SON 1979–2001 (Fig. 7).

Larger trends are observed over a shorter period of time, due to a change of sign after 1978. E.g. CAPE increases by...
about 1300 J/kg per decade in Mexico and in central USA during JJA 1958–1978 and decreases by 200 to 500 J/kg per decade during JJA 1979–2001 (Fig. 7). This change of sign yields in a net increase by 200 to 600 J/kg per decade during JJA 1958–2001. The change of sign is also observed in central Africa as well as in Malaysia and Venezuela if the southern hemisphere is considered before 1978.

Trends in CAPE can be primarily attributed to trends in near surface specific humidity (not shown). Exceptions are central Asia and the east of the USA. A negative trend in specific humidity of −0.1 to −0.01 g/kg per decade is observed during MAM 1958–2001 in central Asia (A negative trend in near surface temperature is observed, too.), whereas a positive trend in CAPE of 20 to 30 J/kg per decade occurs during MAM 1958–2001. In addition, specific humidity shows a non significant positive trend of about 0.01 to 0.1 g/kg per decade in the east of the USA during MAM 1958–2001 (A non significant positive trend in near surface temperature is observed, too.), whereas a negative trend in CAPE of −10 J/kg per decade occurs during MAM 1958–2001. More exceptions are present if we consider trends in the southern hemisphere (mainly in Brazil) prior to 1978. A correlation between changes in CAPE and changes in surface specific humidity is confirmed by Trapp et al. (2007) in the USA in future climate scenarios. Williams and Renno (1993) and Ye et al. (1998) confirm the correlation between surface wet bulb temperature and therefore humidity in the tropics during the present climate.

Trends in CIN occur generally in regions that show trends in CAPE. However, trends in CIN show reversed signs compared to trends of CAPE particularly during JJA and SON. One very distinct example is the region of central Africa throughout the year during 1979–2001. An increase in CAPE is seen, whereas CIN shows a decrease. Larger changes in CIN also occur during the shorter time periods analysed. The largest decrease of about 190 J/kg per decade occurs over the Atlantic, south of Portugal, during JJA 1958–1978. The largest increase of about 100 J/kg per decade is shown over the

Fig. 6. Seasonal trends of CAPE in J/kg per decade, significant at the 95% level. DJF (a, b, c), and MAM (d, e, f) during 1958–2001 (a, d), 1958–1978 (b, e), and 1979–2001 (c, f).
Paci, to the west of Mexico, during MAM 1979–2001. In contrast to these values, CIN trends range from about −60 to 60 J/kg per decade during 1958–2001. Therefore, the change of sign applies also to CIN, although not as pronounced due to generally smaller values of CIN. This change of sign is most distinct also in Mexico and central USA during JJA, central Africa during every season, and in Brazil during JJA and SON.

4. Summary and conclusions

A global climatology of CAPE and its opponent parameter CIN are analysed. The climatology consists of seasonal means, inter annual variances, and trends. Although CAPE and CIN are calculated from basically the same equation applied to different vertical levels, their temporal and spatial distribution differ relatively strong. The climatological means of CAPE increase with decreasing latitude and show largest values close to the ITCZ. Largest values of CIN do not occur close to the ITCZ but between the equator and the 30th latitude revealing a bimodal zonal distribution, therefore resembling the ascending and descending parts of the Hadley Cell.

CAPE shows a strong dependency on near surface specific humidity, while the sensitivity on near surface temperature is not as strongly pronounced. This is reflected in the CAPE pole-to-equator gradient, which resembles the humidity distribution closer than the temperature distribution. These results confirm those of Williams and Renno (1993) and Ye et al. (1998), who point out the correlation between CAPE and humidity in the USA respectively the tropics.

The annual cycle of CAPE generally reaches its maximum during the summer months (northern hemisphere: JJA; southern hemisphere: DJF). However, in the Great Plains, the south of Chile, and the coast of India CAPE develops its largest values in MAM according to moisture availability, also revealing the global link between CAPE and humidity.

The dependency of CAPE on humidity is also visible in the trend analysis. Significant trends in CAPE and CIN occur on
every continent, over every ocean, and during every season. In general, a CAPE increase is noted during all seasons, whereas CIN shows a general increase from December to August and a decrease during autumn. Regarding genesis and intensity of convection, both an increase in CAPE and a decrease in CIN would lead to a higher probability. However, an increase in CAPE and CIN would lead to a higher probability of stronger convection combined with the need of stronger forcings to overcome enhanced stable surface conditions. The observed increase in CAPE combined with a decrease in CIN during autumn (northern hemisphere: SON, southern hemisphere: MAM) indicate that the rain season elongates.

Trends in CAPE as consequence of changes in surface specific humidity in the USA during future climate scenarios are found by Trapp et al. (2007). Our analyses show that this statement is transferable to the present climate (last decades) on a global basis.

Fig. 8. Seasonal trends of CIN in J/kg per decade, significant at the 95% level. DJF (a, b, c), and MAM (d, e, f) during 1958–2001 (a, d), 1958–1978 (b, e), and 1979–2001 (c, f).

Trends in CAPE and CIN (and in near surface temperature and specific humidity) show a change of sign after about 20 years in several regions resulting in a smaller net trend over the whole time series. According to Bengtsson et al. (2004) an artificial trend in temperature and humidity generated by changing measurement systems leads to an offset, which is most pronounced in the southern hemisphere (Simmons et al., 2004). Therefore, the reversal of the trend in the southern hemisphere is probably not an artefact of changing measurement systems, because the offset would not lead to a change of sign.

The reversal of the trend in the second half of the time series may also be contributed to low frequency variability. Yano et al. (2001) found low frequency variability (1/f noise) in CAPE, temperature, and moisture in the tropics for a 4-month period over the western Pacific during the Tropical Ocean and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment. Therefore, the analysis of low frequency variability in
CAPE is in the focus of future studies, on the basis of global and longer data sets.

Acknowledgements

Thanks to Richard Blender and Nikolai Dotzek for most helpful discussions, to Frank Sielmann for his support in CAPE calculation, to DKRZ, DWD, and ECMWF for the data. K. R.-C. acknowledges the support by IMPRS-ESM.

References


Fig. 9. Seasonal trends of CIN in J/kg per decade, significant at the 95% level. JJA (a, b, c), and SON (d, e, f) during 1958–2001 (a, d), 1958–1970 (b, e), and 1979–2001 (c, f).


